UNCLASSIFIED

AD NUMBER
ADB056363
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; FEB 1981. Other requests shall be referred to Army Armament Research and Development Command, Attn: DRDAR-TSS, Dover, NJ 07801.**
AUTHORITY
usaardcom, ltr, 24 nov 1982

THIS PAGE IS UNCLASSIFIED

AD E400-544

CONTRACTOR REPORT ARLCD-CR-80058

FEASIBILITY OF CERAMIC LINED GUN TUBE

ROBERT A . GILES
ERNST BUNNING DAVE CLAXTON
SACO DEFENSE SYSTEMS DIVISION
MAREMONT CORPORATION
291 NORTH STREET
SACO, ME 04072

JOSEPH A. LANNON
PROJECT ENGINEER
ARRADCOM

FEBRUARY 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER
WEAPON SYSTEMS LABORATORY
DOVER, NEW JERSEY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARLCD-CR-80058	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FEASIBILITY OF CERAMIC LINED GUN TUBE		5. TYPE OF REPORT & PERIOD COVERED Final - December 1978 to August 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R.A. Giles, E. Bunning, D. Claxton, MAREMONT; Joseph A. Lannon, Project Engr., ARRADCOM		8. CONTRACT OR GRANT NUMBER(s) DAAK10-79-C-0036
9. PERFORMING ORGANIZATION NAME AND ADDRESS Saco Defense Systems Division, Maremont Corporation, 291 North St., Saco, ME 04072		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS ARRADCOM, TSD, STINFO Div (DRDAR-TSS), Dover, NJ 07801		12. REPORT DATE February 1981
		13. NUMBER OF PAGES 42
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) ARRADCOM, LCWSL, Applied Sciences Div (DRDAR-LCA), Dover, NJ 07801		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; February 1981. Other requests of this document must be referred to ARRADCOM, ATTN: DRDAR-TSS, Dover, NJ 07801

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Wear and Erosion
Ceramic Liners
Improved Gun Barrel
Wear and Erosion
0.50 Caliber Gun

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A feasibility study was initiated to evaluate use of a ceramic liner to prevent rapid wear and erosion of the tube bore. An alpha silicon carbide liner was fabricated, inserted into a barrel, and test fired successfully. The liner performance provides support for further investigation and testing.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SUMMARY

Wear and erosion of gun tubes in many weapon systems limit the life of a gun tube to a relatively small percentage of its fatigue life. Future gun systems, with their requirements for longer range, higher velocity, and more rapid rates of fire, will aggravate the short barrel life. In recognition of the potential for improving barrel life through the application of high melting point materials, this initial study was undertaken to determine whether a ceramic lined barrel is feasible under limited firing conditions.

Based on a review of the properties and the availability of various candidate materials, an alpha silicon carbide material was chosen, fabricated into .50 caliber liners, and subjected to firing tests.

Techniques for encapsulating the ceramic material in a steel sleeve subsequently assembled within a test barrel were developed and proven to be practical.

Test firings of 1,000 rounds of ball ammunition have been made on one barrel. The test results demonstrate that a ceramic liner can be incorporated into the design of a weapon barrel and that such a liner offers high potential for significantly extending barrel life by reducing wear and erosion associated with the firing of a projectile through the barrel.

It is recommended this work be further pursued in the 20 mm 30 mm size with the objective of evaluating the practicality of rifling the ceramic liner and determining its life potential in the automatic firing mode with rates of fire of approximately 600 rounds per minute.

CONTENTS

TABLES

FIGURES

INTRODUCTION

The objective of this study was to establish the feasibility of ceramic lined barrels under limited firing conditions by:

1. Fabricating liners from silicon nitride, silicon carbide or other ceramic materials.

2. Placing these liners into chromium-molybdenum-vandium steel sleeves for placement into chrome-molybdenum-vanadium steel jackets for .50 caliber gun barrels.

3. Test firing ceramic liner barrels, single shot at room temperature, to determine the integrity of the ceramic liner.

PROGRAM FOR ACCOMPLISHMENT OF THE STUDY

The program for the evaluation was broken down into principal elements as follows:

1. Select ceramic liner material.

2. Optimize the liner, sleeve and jacket geometry.

3. Analyze projectile obturation during passage through the liner.

4. Design, procure and inspect the ceramic liners.

5. Determine ceramic liner shrink fit characteristics.

6. Design, fabricate and assemble barrels with ceramic liners.

7. Test fire barrels.

8. Analyze firing results and related data. Prepare final report.

SELECTION OF CERAMIC LINER MATERIAL

Proper material selection was of primary importance. Among the characteristics which the material selected for this application had to exhibit were high thermal shock resistance, chemical inertness, good tensile and compressive strength, a coefficient of expansion compatible with that of steel, and commercial availability in the desired sizes and shapes. A decision was made to select the best commercially available ceramic material even though material with superior properties might be available on a laboratory basis.

Initial consideration was given to Coors AD-999 Alumina; however, further investigation revealed two other more promising candidates in the form of hot pressed silicon nitride (Kawecki Berylco, Industries, Inc. - Reading, PA) and alpha silicon carbide (Carborundum Co. - Niagara Falls, New York). A comparison of the important properties of these materials with those of Stellite 21 and Cr, Mo, V barrel steel, is shown in table 1. After reviewing these properties, sintered alpha silicon carbide was selected as the material to be used. This choice was based primarily on its superior thermal shock resistance, good tensile and compressive strength, and ready availability. Alpha silicon carbide's good thermal shock index is the result of its surprisingly high thermal conductivity which compares favorably with that of steel. Measurements performed at the Army Materials and Mechanics Research Center on test pieces representative of the alpha silicon carbide liners indicated that the properties of the material in the liner configuration were equal to those measured on bulk test samples and published by Carborundum as product literature.

The thermal gradient, as calculated by Calspan for various materials under single shot firing conditions is shown in figure 1. This figure does not contain a curve for alpha silicon carbide; however, based on similar thermal conductivities, the thermal gradient for this material is expected to be similar to that shown for Cr, Mo, V steel. High thermal conductivity results in a flatter thermal gradient and, therefore, lower peak thermal stresses at the bore surface (figure 2).

Table 1. Comparative properties of liner and barrel materials

	AD-999 Alumina	Hot pressed silicon nitride	Sintered alpha silicon carbide	Haynes Stellite No. 21	CR, MO, V gun steel
Thermal Conductivity °F BTU-IN/°F/hr/ft^2 (C)	43.5	97.2	343.0	160	324*
Modulus of Rupture (psi) (R)	45,000	100,000	64,100		
Young's Modulus (psi) (E)	56×10^6	45×10^6	59.4×10^6	32×10^6	30×10^6*
Coef. of Thermal °F Expansion (A)	4.1×10^{-6}	2.0×10^{-6}	2.67×10^{-6}	8.68×10^{-6}	6.3×10^{-6}*
TS Thermal Shock °F Index	$.85 \times 10^4$	10.8×10^4	13.9×10^4		
TS (Adjusted) °F	1	12.7	16.3		
Poisson's Ratio	0.22	0.24	0.142		0.30*
Tensile strength (psi)	32,000	57,000	48,000	62,000	20,000
Compressive Strength (psi)	280,000	400,000	500,000		

All properties at 1472°F unless otherwise noted

$$TS = \frac{C \times R}{E \times A}$$

*Ambient

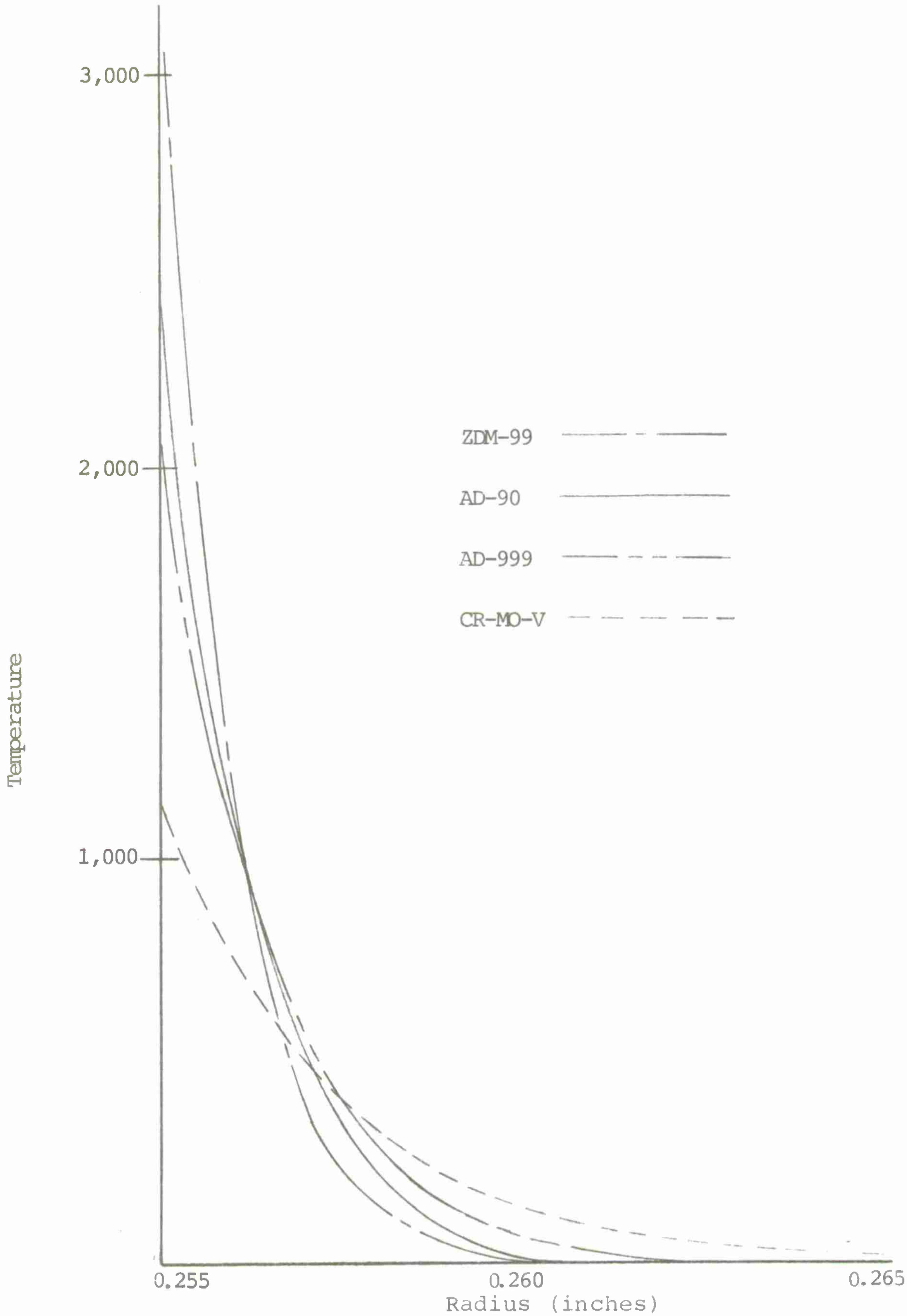


Figure 1: Temperautre vs. radius (First shot condition)

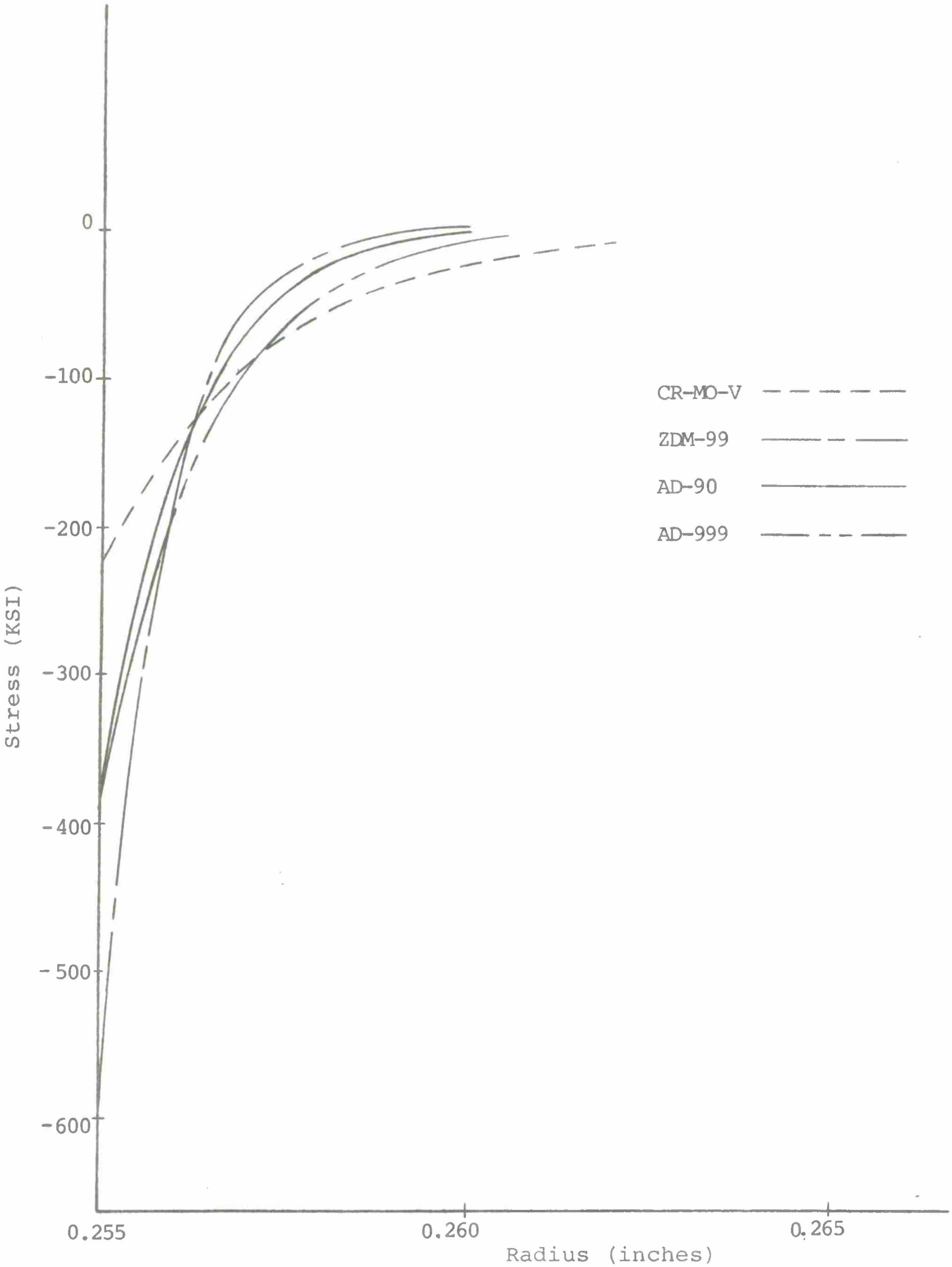


Figure 2: Tangential stress vs. radius
(First shot condition)

OPTIMIZATION ANALYSIS OF THE LINER, SLEEVE & JACKET GEOMETRY

The objective of the analysis and optimization effort was to arrive at a liner/sleeve/jacket configuration and interference fits which would:

1. Maintain the alpha silicon carbide liner under compressive stress at all times.

2. Maintain tensile stresses in the liner and jacket at moderate levels.

3. Maximize the ease of assembly by minimizing the required interference fits.

A computer program was written which calculates theoretical radial, tangential and axial stresses at the bore, the liner OD, sleeve ID, sleeve OD, jacket ID, and jacket OD, given the following input data:

1. Bore radius
2. Radius at 1st joint
3. Radius at 2nd joint
4. Outside radius
5. Young's modulus of liner
6. Young's modulus of sleeve
7. Young's modulus of jacket
8. Poisson's Ratio of liner
9. Poisson's Ratio of sleeve
10. Poisson's Ratio of jacket
11. Interference at 1st joint
12. Interference at 2nd joint
13. Coefficient of expansion-liner
14. Coefficient of expansion-sleeve
15. Coefficient of expansion-jacket

16. Coefficient of friction-liner/sleeve

17. Coefficient of friction-sleeve/jacket

18. Bore pressure

This program is also capable, with minor modification, of calculating these stresses at elevated temperatures. While beyond the scope of this study, this feature will be useful in any future work since differences in the coefficient of thermal expansion cause the stress pattern to change.

Various computer runs were made with the liner outside radius at 0.355 in., 0.405 in., and 0.465 in. For each of these dimensions, computer runs were made with the sleeve outside radius at 0.505 in., 0.660 in., and 0.765 in. For each of these combinations the diametral interference fits between liner and sleeve and sleeve and jacket were varied between 0.002 in. and 0.004 in. A complete listing of the various combinations run and the resulting stress values are shown in table 2.

Figure 3 is a copy of a typical computer printout showing the input/output information for an assembly with a 0.004 in. diametral interference between liner and sleeve, and 0.002 in. between sleeve and jacket. Figure 4 is a graphical presentation of the radial and tangetial stresses calculated by the computer program. Line 1 shows just the shrink fit stresses. Line 2 shows the stresses due to pressure from firing and Line 3 shows the resultant when these two stresses are superimposed. Note that the radial stresses are compressive in all elements at all locations. The tangential stresses on the liner are -85,700 psi (compressive) at the bore and the jacket sees a maximum stress of +83,581 psi (tensile).

The theoretical axial stresses for the same assembly are shown in figure 5. The maximum stresses are -97,243 psi (compressive) in the liner, +16,113 psi (tensile) in the sleeve, and +22,405 psi (tensile) in the jacket. Stresses are a maximum at the midpoint, decreasing to a minimum at each end.

Figure 6 provides a graphical presentation of the change in tangential stress at the bore surface with variation in liner and sleeve diameter for two different interference fits between liner and sleeve. As might be expected, stress at the bore increases with increasing interference and decreasing liner and sleeve OD.

Figure 7 shows, for a given configuration, the change in tangential stress at the bore surface resulting from a

Table 2. Radial, tangential, and axial stress for various liner/sleeve configurations and interference fits

Radius (inches)				Diametrel Interference (in.)		Radial stress (KSI)				Tangential stress (KSI)						Axial stress (KSI)		
											B	B	C	C				
A	B	C	D	Liner sleeve	Sleeve jacket	A	B	C	D	A	Inner	Outer	Inner	Outer	D	A	B	C
0.255	0.355	0.505	0.965	0.002	0.002	-55000	-61345	-38076	0	-172738*	-130933*	30659	7390	66796	28720	-147730	-23993	17904
				0.004	0.002	-55000	-87632	-48985	0	-281355	-213263*	65175	26527	85933	36949	-192335	9441	15549
				0.002	0.004	-55000	-76864	-57134	0	-236810	-179536	-24509	-32809*	100229	43094	-250884	-34913	29290
0.255	0.355	0.660	0.965	0.002	0.002	-55000	-54530	-19653	0	-144578*	-109588*	43621	8744	54198	34545	-162904	4515	17230
				0.004	0.002	-55000	-80817	-24334	0	-253194*	-191917*	78136	21653	67108	42774	-276089	18833	22217
				0.002	0.004	-55000	-63233	-31145	0	-180538*	-136845*	27069	-14615*	85890	54745	-203424	- 7101	28472
0.255	0.355	0.765	0.965	0.002	0.002	-55000	-51069	-11337	0	-130275*	- 98747*	50203	10471	49687	38350	-146789	6800	16854
				0.004	0.002	-55000	-77356	-13769	0	-238892*	-181077*	84719	21132	60348	46579	-269174	19816	21157
				0.002	0.004	-55000	-56310	-18433	0	-151934	-115164	40235	- 5567*	80789	62356	-171194	584	29472
0.255	0.405	0.505	0.965	0.002	0.002	-55000	-57122	-41723	0	-144919*	-101185*	29188	13789	73195	31471	- 88421	-24114	16191
				0.004	0.002	-55000	-82745	-56248	0	-229822*	-160466*	65767	39270	98676	42428	- 76563	23130	8097
				0.002	0.004	-55000	-75234	-61332	0	-204973	-143088*	-16429*	-24532*	107594	46262	-188699	-33305	32109
0.255	0.405	0.660	0.965	0.002	0.002	-55000	-49168	-21114	0	-118501*	- 82782*	40828	12774	58228	37124	-117098	7968	19024
				0.004	0.002	-55000	-74791	-27347	0	- 20346*	-142063*	77406	29963	75417	48070	-170771	15416	25664
				0.002	0.004	-55000	-59326	-32739	0	-152219*	-106282	25964	- 9605*	90286	57547	-150340	- 2514	31408
0.255	0.405	0.765	0.965	0.002	0.002	-55000	-45290	-12609	0	-150175*	- 73434*	46739	13680	52895	40826	-130877	9339	18354
				0.004	0.002	-55000	-70751	-15308	0	-190079*	-132717*	83318	27874	67090	51783	-187733	24342	24082
				0.002	0.004	-55000	-51246	-19207	0	-125447*	- 87589*	37787	5747	84179	64972	-123898	3673	30979
0.255	0.465	0.505	0.965	0.002	0.002	-55000	-51691	-45723	0	-122188*	- 79467*	26774	20805	80211	34488	- 47063	-18466	11583
				0.004	0.002	-55000	-74527	-64033	0	-187501*	-121944*	63421	52927	112333	48300	3058	32970	-2575
				0.002	0.004	-55000	-71577	-65942	0	-179064	-116457	-11891	-15749*	115681	49739	-144246	-46903	35100
0.255	0.465	0.660	0.965	0.002	0.002	-55000	-42958	-22715	0	- 97210*	- 63222*	37432	17489	62655	39928	- 81114	8663	20911
				0.004	0.002	-55000	-66794	-30573	0	-162527*	-105699*	74079	38858	84313	53740	- 94652	56309	21657
				0.002	0.004	-55000	-54110	-34487	0	-129107*	- 83966*	23821	- 4314*	95107	60620	-111060	971	33451
0.255	0.465	0.765	0.965	0.002	0.002	-55000	-38523	-12870	0	- 84524*	- 54971*	42845	11913	56408	43538	- 72709	11107	19928
				0.004	0.002	-55000	-61358	-16953	0	-149836*	- 97448*	79492	35087	74303	57350	-116816	22408	27150
				0.002	0.004	-55000	-45240	-20054	0	-103735*	- 67466*	34648	9462	87893	67839	- 89235	5964	32635

* Maximum stress is due to shrink fit only

INPUT VALUES

BORE RADIUS	0.255	INTERFERENCE AT 1ST JOINT	0.00400
RADIUS AT 1ST JOINT	0.465	INTERFERENCE AT 2ND JOINT	0.00200
RADIUS AT 2ND JOINT	0.660	LINER THERM. COEFF.	0.00000223
OUTSIDE RADIUS	0.965	SLEEVE THERM. COEFF.	0.00000700
YOUNGS MODULUS OF LINER	56000000.	JACKET THERM. COEFF.	0.00000700
YOUNGS MODULUS OF SLEEVE	30000000.	COEFF. OF FRIC. BETW LINER + SLEEVE	0.20
YOUNGS MODULUS OF JACKET	30000000.	COEFF. OF FRIC. BETW. SLEEVE + JACKET	0.20
POISSONS RATIO OF LINER	0.14	BORE PRESSURE	55000.
POISSONS RATIO OF SLEEVE	0.30		
POISSONS RATIO OF JACKET	0.30		

	RADIAL STRESSES				TANGENTIAL STRESSES					
	AT BORE	AT FIRST JOINT	AT SECOND JOINT	AT OUTER SURFACE	AT BORE	AT FIRST JOINT IN LINER	AT FIRST JOINT IN SLEEVE	AT SECOND JOINT IN SLEEVE	AT SECOND JOINT IN JACKET	AT OUTER SURFACE
PRESSURE STRESSES	-55000.	-8970.	-3086.	0.	76651.	30621.	14395.	8512.	8512.	5425.
COLD SHRINK STRESSES	0.	-56824.	-27486.	0.	-162522.	-105699.	59684.	30346.	75801.	48315.
9 TOTALS	-55000.	-65794.	-30573.	0.	-85871.	-75078.	74079.	38858.	84313.	53740.
2-TUBE ASSEMBLY COLD SHRINK STRESSES	0.	-30783.	0.		-88042.	-57260.	91464.	60682.		

AXIAL STRESSES

	2-TUBE ASSEMBLY	SLIPS?	3-TUBE ASSEMBLY	SLIPS?.
LOAD IN LINER - LB	-35975.	YES	-44960.	NO
STRESS IN LINER - PSI	-75735.		-94652.	
LOAD IN SLEEVE - LB	35975.		11240.	
STRESS IN SLEEVE - PSI	52199.		16309.	
LOAD IN JACKET - LB			33721.	NO
STRESS IN JACKET - PSI			21657.	

FOLLOWING ARE THE LOADS WHICH WOULD OCCUR IN THE ELEMENTS IF THERE WERE NO SLIPPAGE WHATSOEVER:

2-TUBE ASSY IN THE LINER -65846. IN THE SLEEVE 65846.

3-TUBE ASSY IN THE LINER -44960. IN THE SLEEVE 11240. IN THE JACKET 33721.

Figure 3: Sample computer run

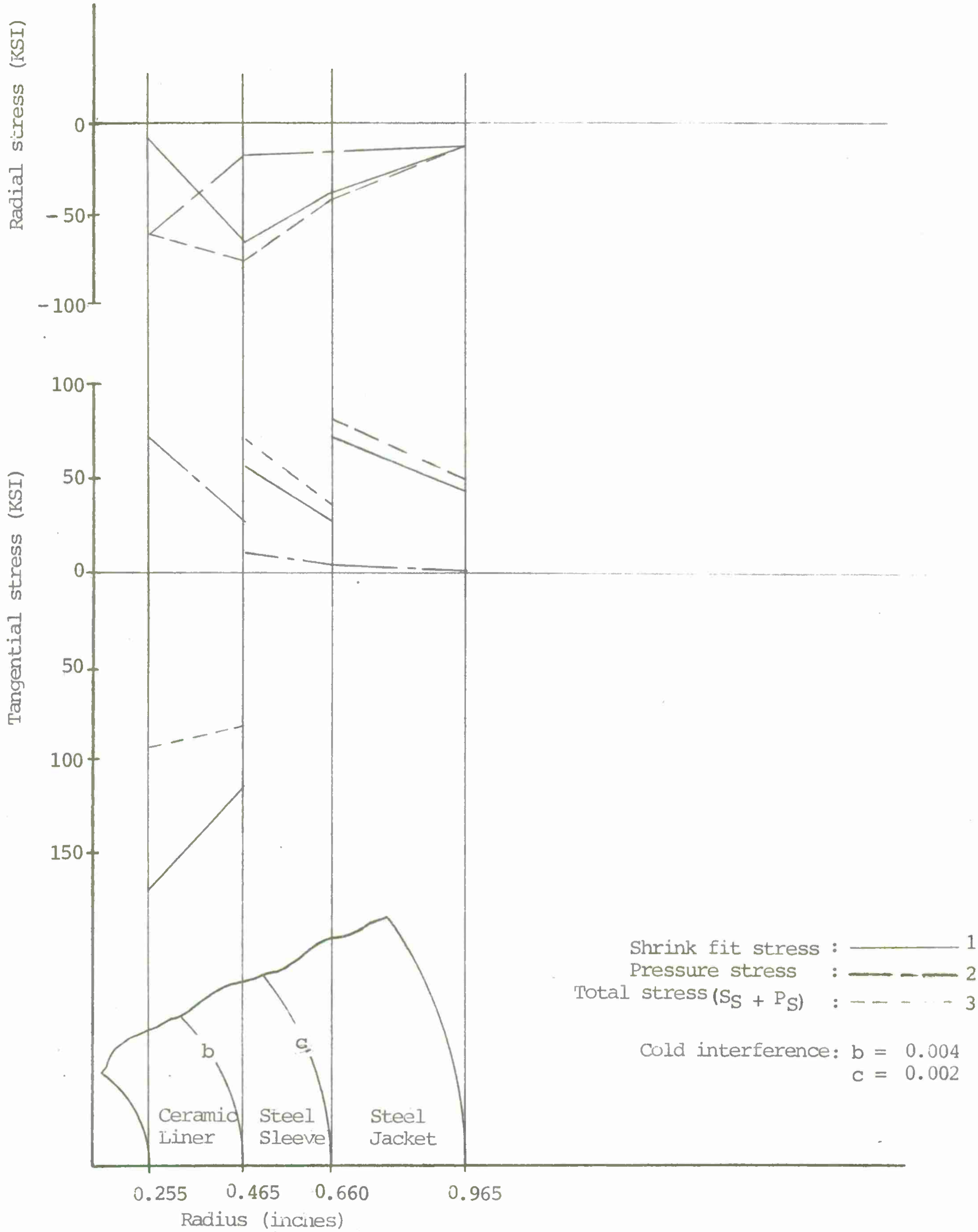


Figure 4. Barrel with liner - stress patterns

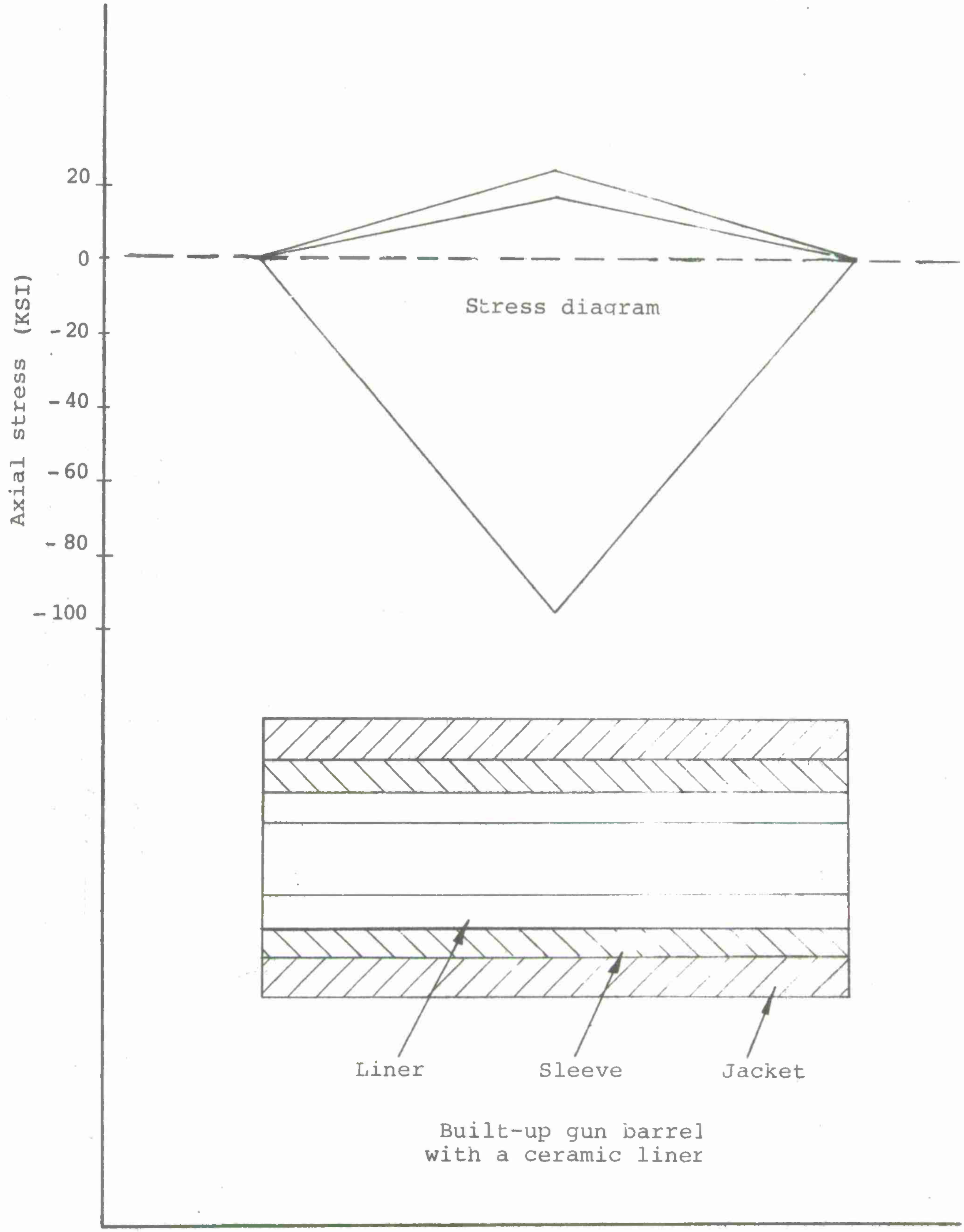


Figure 5: Axial stress induced by shrinkage process

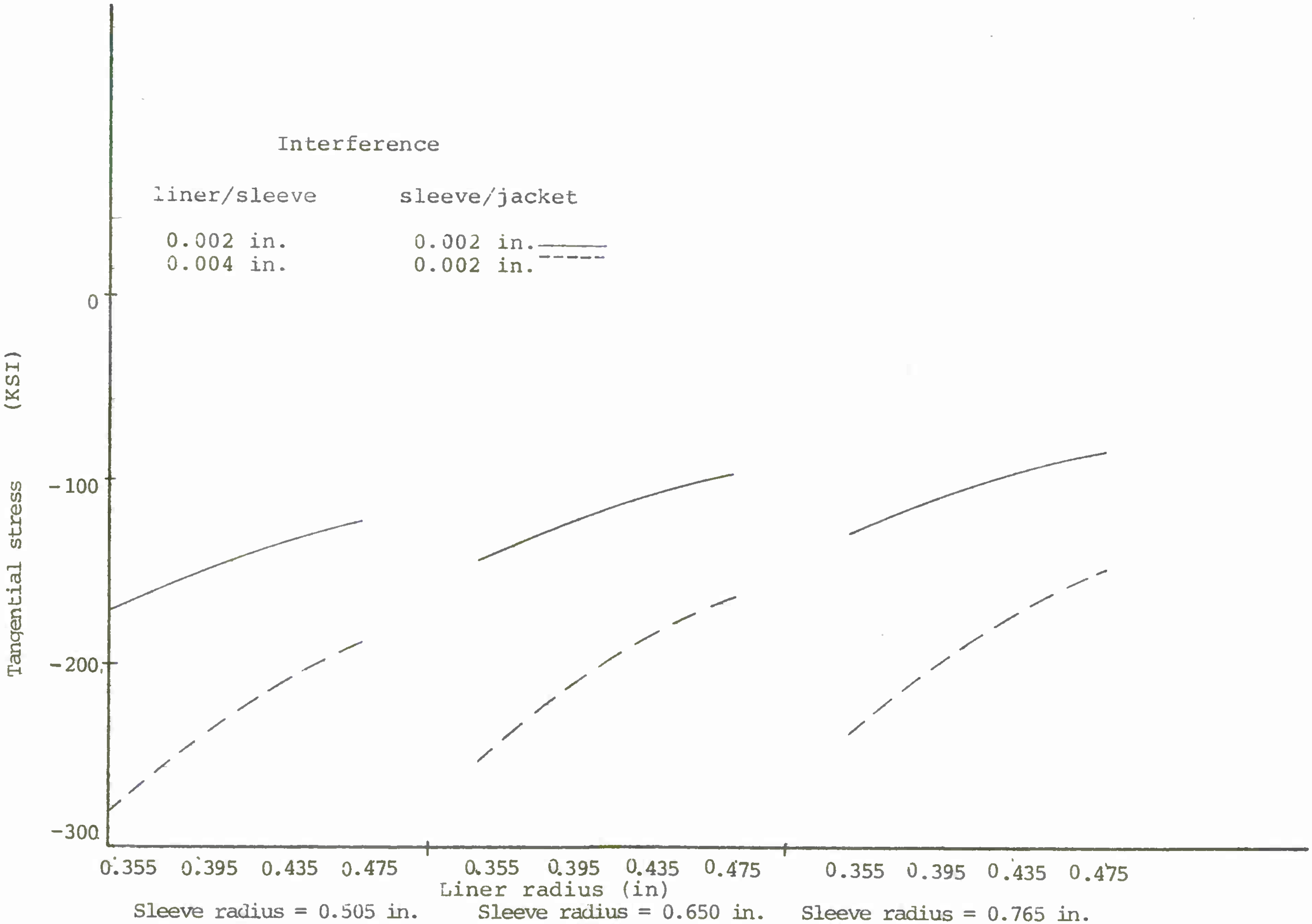


Figure 6. Tangential stress - interference fits vs. joint radius

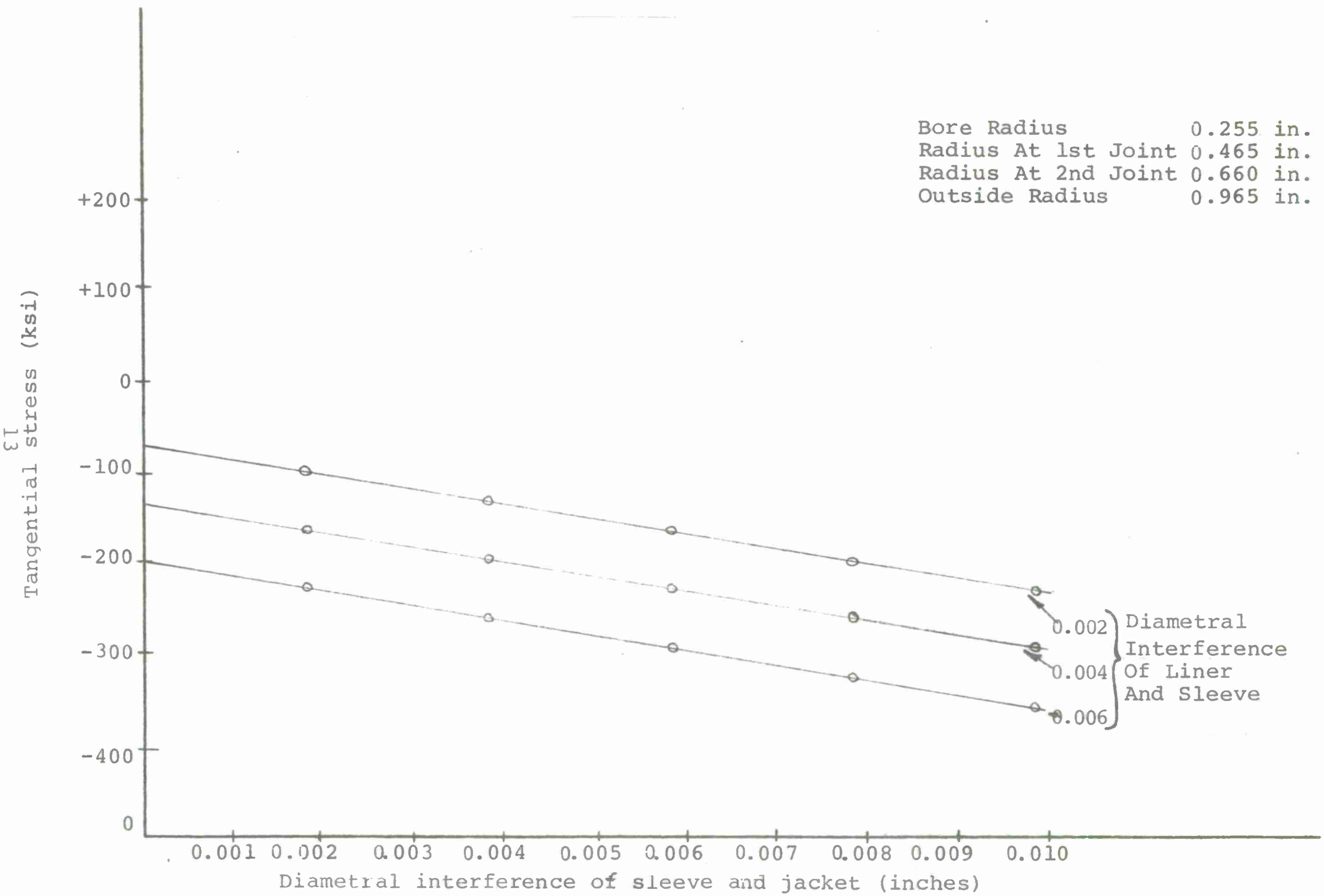


Figure 7. Tangential stress at liner bore vs. interference fit

change in interference fit between liner and sleeve and sleeve and jacket. Note that the change in stress for a given change in liner/sleeve interference is approximately twice that for the same change in sleeve/jacket interference.

The results of the stress analysis indicate that there is a relatively wide range of diameters and interference fits over which acceptable stress values can be obtained. This range will undoubtedly be narrowed considerably when elevated temperature conditions are considered. It was decided, however, that the assemblies to be tested at relatively low temperature during the first phase of this program would consist of a liner with a nominal 0.510 in. ID and 0.930 in. OD and a sleeve with a 0.930 in. ID and 1.23 in. OD. The jacket OD was selected to be 1.910 in. Diametral interference fits between liner and sleeve were to be varied between 0.002 - 0.004 in., while the interference between sleeve and jacket would be maintained at 0.002 in.

The length of the liner was established at 8 in. since this was as close to the length of the present .50 caliber liner that any vendor was willing to produce. A 4 in. length was also established for use in the event the 8 in. liner proved impractical. The shorter liner would be easier to assemble should the 8 in. length prove difficult to handle.

BULLET OBTURATION TEST

The ceramic liners used in this program have smooth bores with a slight clearance fit with the projectile. One area which does not lend itself to analysis is the loading that the projectile exerts on the liner wall. This loading could result from the projectile "slapping up" against the liner wall as it travels down the bore or through pressure stresses expanding the projectile to put high friction forces on the liner ID.

A bullet obturation test was conducted in an attempt to determine the probable friction forces exerted by the projectile on the liner walls. This test consisted of firing a projectile from a short barrel section corresponding in length and bore diameter to the ceramic liner, catching it in a bullet trap and measuring the increase in bullet diameter. There was no detectable expansion and therefore, the frictional forces to be felt by the ceramic liner surface as a result of the projectile passage are considered to be minor.

PROCUREMENT AND INSPECTION OF LINERS

After considerable research, Carborundum Co., Niagara Falls, N.Y., was chosed as the source for the silicon carbide liners to be test fired. This choice was based in large part on the fact that Carborundum was the only one of the potential suppliers producing this material on a production basis and one of only two suppliers willing to furnish parts finished to our drawing No. MB 3499. An order was placed with Carborundum on March 8, 1979.

In early May 1979, following a review meeting at Maremont, Dr. J. McCauley and Mr. R. N. Katz of the Ceramics Research Division of the Army Materials and Mechanics Research Center offered to provide valuable assistance in characterizing the ceramic liners prior to test firing. To provide the necessary one inch test pieces, our order with Carborundum was modified to reduce the liner length from 8 inches to 7 inches.

Liners and test pieces were received from Carborundum as shown below:

Received	P.O. No.	One Inch	Four Inch	Seven Inch
11-3-79	19108	6	6	--
1-2-79	11123	10	6	10
4-17-80	11123	7	8	--
	Total Received	23	20	10

Specimens were inspected as indicated in table 3. Dimensions were obtained by conventional inspection techniques; the IDs were measured using a Sheffield air gage. Surface roughness readings were taken with a Perthen "Perthometer", Model C5D. Specific gravity measurements were taken by the method of ASTM Spec. C773-72, "Compressive (Crushing) Strength of Fired Whiteware Materials", and dye-penetrant inspection was in accordance with MIL-I-6866B, Type I, Method A, "Inspection, Penetrant Method of".

EXPERIMENTAL ASSEMBLY OF LINER AND SLEEVES

The objective of this task was to develop an assembly technique specifically for the liner/sleeve subassembly, as well as to determine whether the alpha silicon carbide

Table 3. Inspection results ceramic liners used in firing tests

Feature		Specimen No. 4 4 inches	Specimen No. 6 4 inches	Specimen No. 12 4 inches
*Inside diameter	End	0.5113/0.5113	0.5112/0.5112	0.5108/0.5108
	Ctr	0.5109/0.5109	0.5110/0.5110	0.5108/0.5108
	End	0.5112/0.5112	0.5112/0.5112	0.5108/0.5108
*Outside diameter	End	0.9300/0.9299	0.9299/0.9299	0.9302/0.9300
	Ctr	0.9296/0.9297	0.9288/0.9297	0.9301/0.9300
	End	0.9299/0.9289	0.9299/0.9299	0.9301/0.9300
Concentricity	End	0.0001	0.0002	0.0005
	End	0.0002	0.0002	0.0006
End squareness	End	0.0005	0.0015	0.0003
	End	0.0008	0.0007	0.0004
Length		0.4006	4.000	4.0048
Specific gravity		3.156	3.248	----
Visual inspection		OK	2 small pits in ends	OK
Dye-penetrant inspection		OK	OK	OK
Surface finish of bore		3-4 r.m.s.	3-4 r.m.s.	----

* Readings taken 90° apart

material could withstand the thermal shock of being brought into intimate contact with a steel sleeve at 900 F.

Significant postponements in the delivery dates for finished liners from Carborundum made it necessary to look for an alternate source of silicon carbide tubular shapes that could be used to work out an assembly technique. Norton Crystar HD cast silicon carbide was found to be readily available in 1 inch OD, 1/2 inch ID tubes at prices substantially below those for alpha silicon carbide. Rather than delay the program further, the decision was made to use Crystar HD in arriving at an experimental assembly procedure. It was reasoned that this material, with properties significantly below those of alpha silicon carbide, would present an even more severe test of our ability to shrink fit liner and sleeves together than was originally planned.

Five four-inch Crystar HD liners were ground to produce an OD of 0.9688 inches and assembly into sleeves having diametral interferences of 0.001 inch, 0.002 inch, 0.003 inch, 0.004 inch, and 0.005 inch respectively. The interferences were effected by varying the inside diameters of the sleeves, i.e., the second sleeve was given a diameter 0.001 inch smaller than the first, etc. The heating medium was a Lepel water-cooled high frequency induction heater. The procedure was to insert the sleeve (held by a suitable fixture) into the induction coil, heat to 950 F, slip the liner into the sleeve, cool to ambient and visually inspect the liner.

After assembly in the sleeves, the ID and end surfaces of all five liners were examined visually and found to be free of damage. It was therefore concluded that silicon carbide liners with diametral interferences up to 0.005 inches can be successfully shrink fitted into steel sleeves heated to 950 F.

In an attempt to determine whether there was any heat checking on the liner OD, the liner/sleeve subassembly was placed in an induction coil and heated to remove the liner. The first two liners (with 0.001 inch and 0.002 inch interferences) were again found by visual inspection to be undamaged. The other three were each found to be broken in two places. This was attributed to uneven heating of the sleeve during the removal process which in turn created a variation in compression and set up shear stresses in sectional planes along the length of the liner.

The results of dimensional measurements taken on liners and sleeves before and after shrink fit tests are tabulated in table 4. A plot of measured versus calculated dimensional changes is shown in figures 8 and 9.

As part of the development of a liner-sleeve assembly technique, an experiment was performed to establish the coefficient of friction between liner and sleeve for input into the computer program, for solution of axial stresses.

A 0.950 inch OD by 0.540 ID by four inch long Crystar HD silicon carbide tube was shrunk into a 1.320 inch OD Cr-Mo-V sleeve of the same length; the diametral interference fit being 0.003 inches. The assembly was then placed in a Tinius-Olsen machine, and the liner was pressed out. A break-free force of 57,400 lb was observed. The innertube cracked and broke in several places, as it was emerging.

Reconciliation of the break-free force of 57,400 lb, and an analytical shrink pressure of 21,700 psi resulted in a coefficient of friction of 0.2.

Crystar HD material was used only for the experimental assembly phase of the program. All liners assembled in subsequent tasks were made from Alpha silicon carbide.

DESIGN, FABRICATION AND ASSEMBLY OF BARRELS FOR FIRING TEST

The barrel assembly designed for use in the firing test is shown in figure 10. This assembly consists of a breech section (containing liner and sleeve) and a muzzle section which slip fits together and are held in position with a retaining nut. This two piece design was selected to facilitate periodic inspection of the liner ID during the firing tests. It should be noted that the sleeve used in this assembly was changed from the straight cylindrical design used in the shrink fit test to a two diameter sleeve with an internal shoulder (figure 11). This revised design has the advantage of making the liner/sleeve assembly self-fixturing as well as facilitating the maintainance of close concentricity between the chamber neck and the liner bore.

Initial attempts to assemble alpha silicon carbide liners with the redesigned sleeves using the same techniques employed earlier in the shrink fit tests failed when the liners cracked during cooling. The problem appeared to be associated with nonuniform heating and cooling resulting from the design of the induction coil and the varying section thickness and diameters present in the sleeve. Despite improvements in heating uniformity resulting from redesign in the induction

Table 4. Dimensional measurements for CRYSTAR HD liners and CR, MO, V steel sleeves with varying interference fits

Sleeve number	Interference fit	Sleeve length	Sleeve OD	Sleeve ID
Original dimensions				
1	-----	4.000	1.3200	0.9678
2	-----	4.000	1.3200	0.9668
3	-----	4.000	1.3200	0.9658
4	-----	4.000	1.3200	0.9648
5	-----	4.000	1.3200	0.9638
Dimensions after assembly				
1	0.001	4.0025	1.3205	-----
2	0.002	4.0025	1.3213	-----
3	0.003	4.0023	1.3218	-----
4	0.004	4.0020	1.3226	-----
5	0.005	4.0062	1.3228	-----
Actual change in dimensions				
1	0.001	+0.0025	+0.0005	-----
2	0.002	+0.0025	+0.0013	-----
3	0.003	+0.0023	+0.0018	-----
4	0.004	+0.0020	+0.0026	-----
5	0.005	+0.0062	+0.0028	-----

NOTE: All CRYSTAR HD liners had a 0.9688 inch OD and an cast ½ inch ID

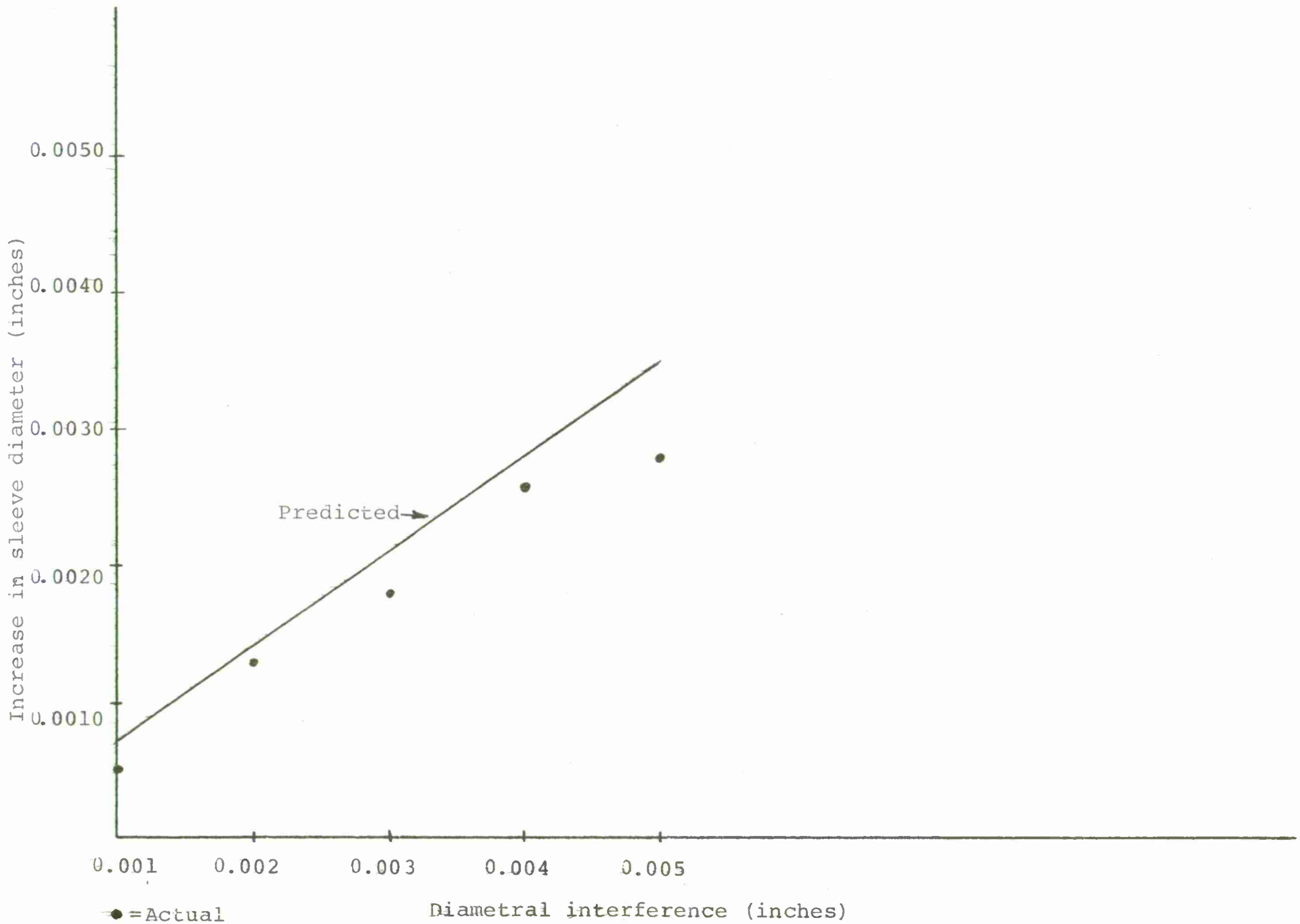


Figure 8. Sleeve diameter changes vs. interference

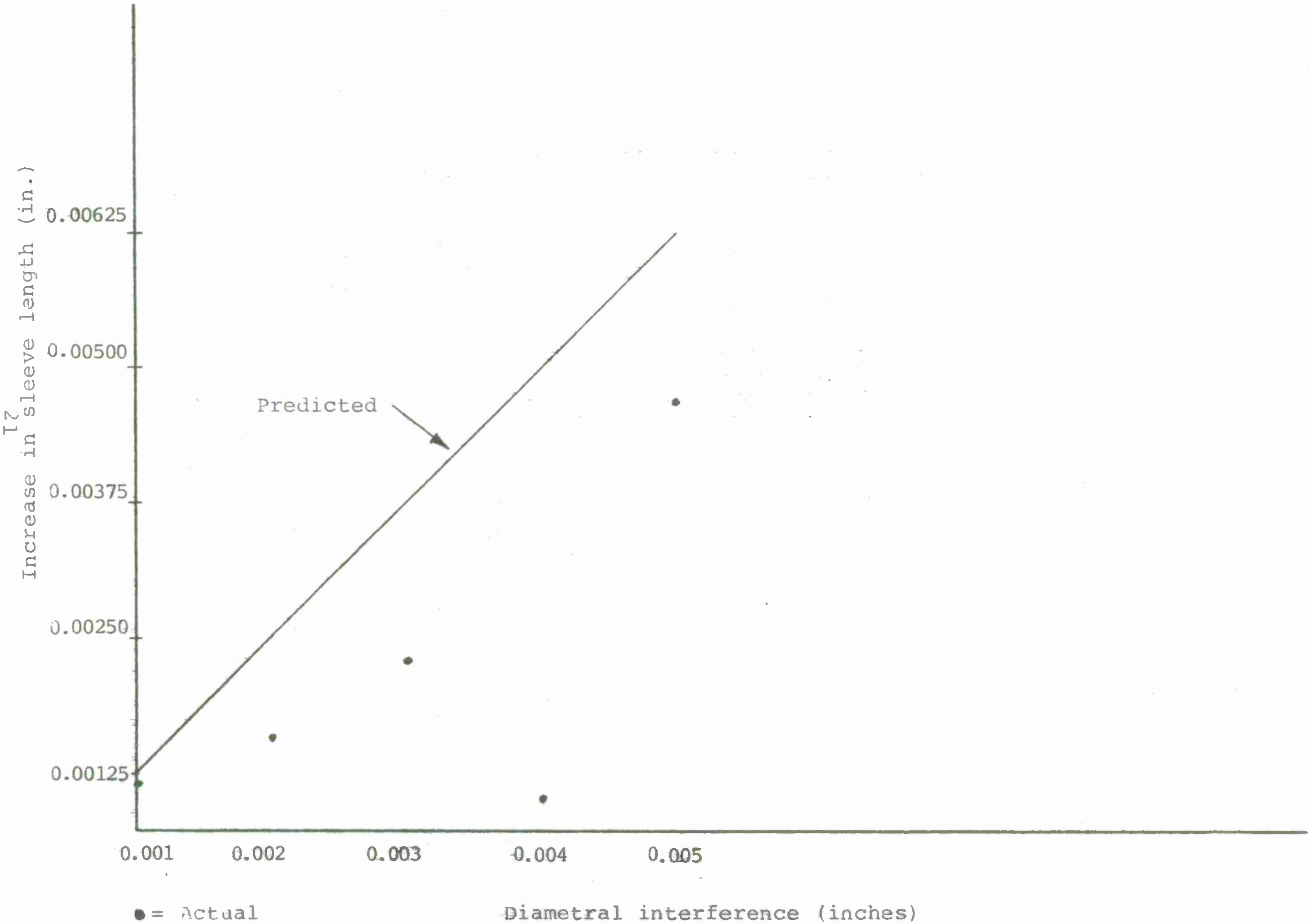


Figure 9. Sleeve length changes vs. interference

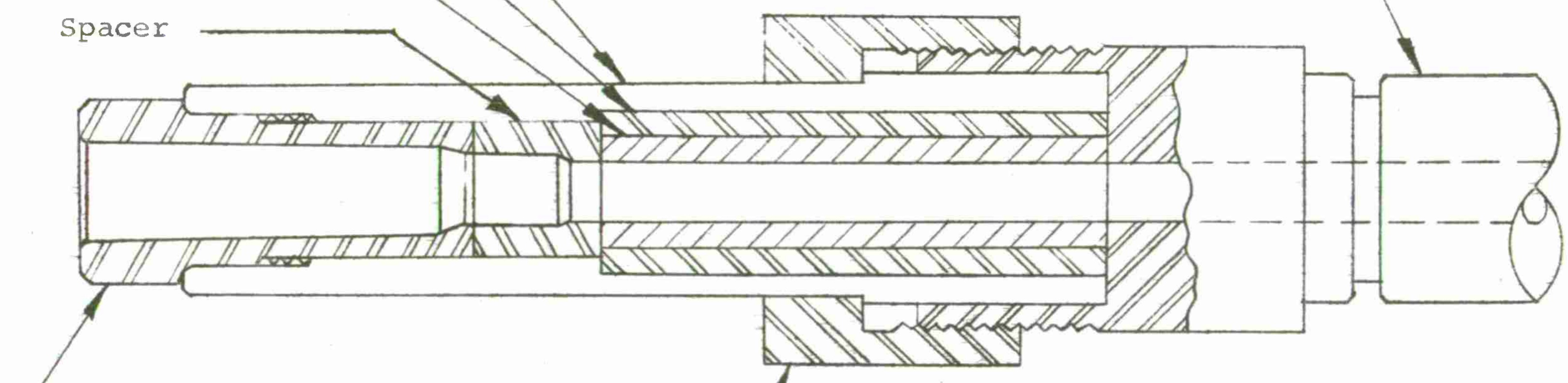


Figure 10. Ceramic liner test barrel assembly first configuration

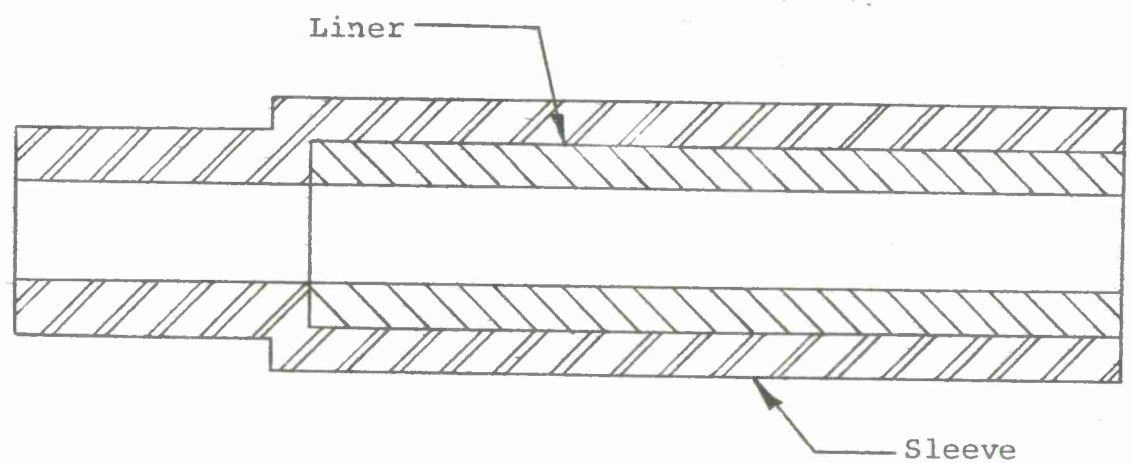


Figure 11. Liner and sleeve assembly revised design

coil, a reduction in the power level and an increase in cycle time, liners could not be assembled without cracking--usually within 1/4 inch from the end.

At this point the decision was made to return to the original sleeve design (figure 12) that had worked successfully in the shrink fit tests and to switch from induction heating and air cooling to forced air convection heating and controlled furnace cooling in an attempt to eliminate temperature gradients and the resulting variations in stress. Oven heating complicated the handling associated with the assembly operation; however, with the aid of a fixture, figure 13, and a few practive runs, assembly of the liner and sleeve became routine.

The assembly of final shooting hardware was now undertaken. Three breech assemblies were prepared--one each with 0.002, 0.003, and 0.004 inch diametral interference between liner and sleeve and all having a 0.002 inch diametral interference between sleeve and jacket. Table 5 shows the dimensional inspection results from the three breech assemblies at various stages of completion. Table 6 shows the change in liner bore diameter due to shrink fit stresses on the three assemblies.

All breech assemblies were subjected to fluorescent penetrant inspection at the completion of the assembly operation. The liner in Assembly No. 1 (0.004 inch interference) was found to contain a circumferential crack running completely around the ID approximately 1/2 inch back from the muzzle end of the liner. This crack was not present after shrink fitting the liner into the sleeve but apparently developed during or after shrink fitting the jacket onto the liner/sleeve subassembly. Assembly Nos. 2 and 3 were found to be free of defects.

Muzzle sections were joined to the breech assemblies by means of retaining nuts. The breech end was heated to facilitate assembly of a spacer and retainer and the barrels were completed by finish chambering. Assembly sequence and techniques were tailored wherever possible to make use of existing .50 caliber barrel manufacturing operations. The test barrel assembly procedure is summarized in figure 14.

During the course of the firing tests, circumstances arose that required certain hardware modifications. This will be dealt with in a subsequent section.

FIRING TESTS

In order to determine whether an alpha silicon carbide barrel liner maintained under compressive stress can survive

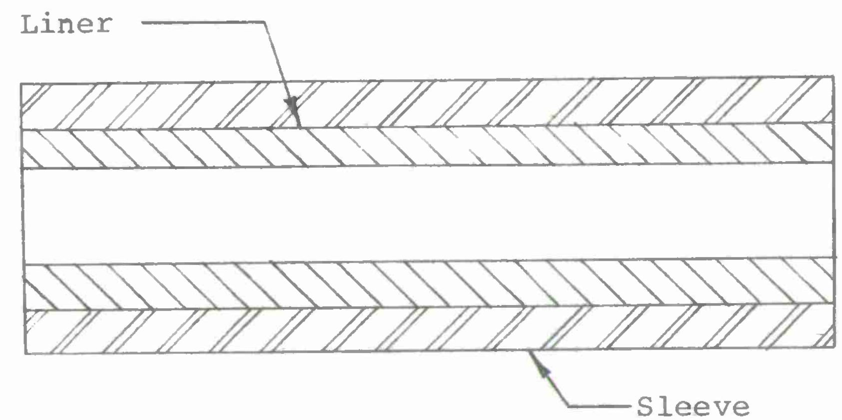


Figure 12. Liner and sleeve assembly - original design

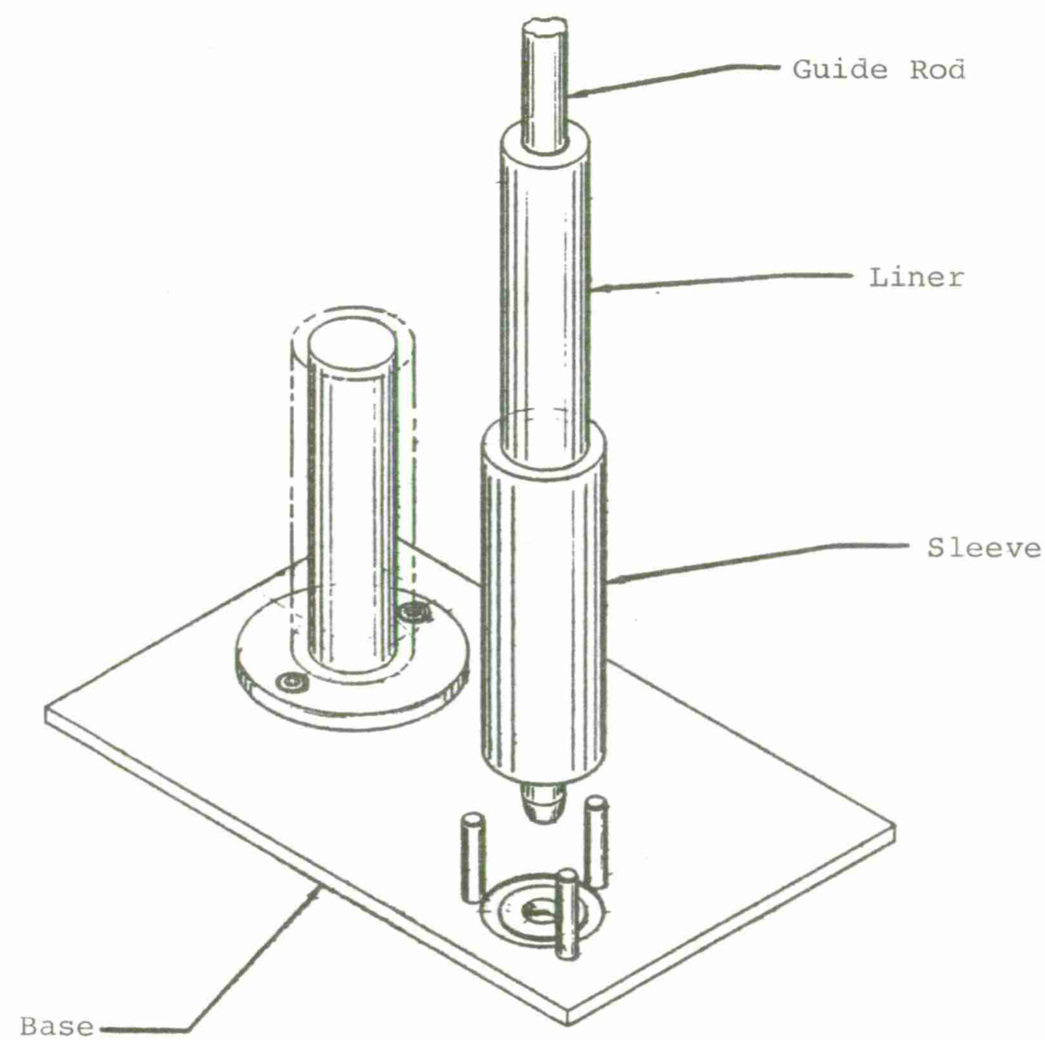


Figure 13. Liner and sleeve assembly fixture

Table 5. Comparisons of dimensions: ASSEMBLY No. 1 thru 3

	Liner		Sleeve		Liner/sleeve assembly		Liner/sleeve/jacket assembly	
	ID	OD	ID	OD	ID	OD	ID	OD
ASSEMBLY No. 1 (-0.004 in.)	#4-4	in.						
Breech	0.5113	0.9299/0.9300	0.9260	1.332	0.5107	1.3317/1.3344	0.5098/0.5100	-----
Middle	0.5109	0.9296/0.9297	0.9262	1.329	0.5102	1.3310/1.3329	0.5097	-----
Muzzle	0.5112	0.9298/0.9299	0.9262	1.330	0.5104	1.3342/1.3367	0.5102/0.5103	-----
Average	0.5111	9.9298	9.9261	1.330	0.5104	1.3335	0.5100	-----
Assembly No. 2 (-0.002 in.)	#6-4	in.						
Breech	0.5112	0.9299	0.9277	1.336	0.5108	1.3374/1.3384	0.5100/0.5102	-----
Middle	0.5110	0.9297/0.9298	0.9276	1.336	0.5104	1.3360/1.3381	0.5100	-----
Muzzle	0.5112	0.9299	0.9278	1.337	0.5108	1.3377/1.3391	0.5105/0.5108	-----
Average	0.5111	0.9298	0.9277	1.3363	0.5107	1.3378	0.5104	-----
Aasembly No. 3 (-0 003 in.)	#12-4	in.						
Breech	0.5108	0.9300/0.9302	0.9270	-----	0.5101	1.3325/1.3335	0.5098	-----
Middle	0.5108	0.9300/0.9301	0.9270	-----	0.5100	1.3325/1.3330	-----	-----
Muzzle	0.5108	0.9310/0.9300	0.9270	-----	0.5102	1.3330/1.3340	0.5098	-----
Average	0.5108	0.9300	0.9270	-----	0.5101	1.3331	0.5098	-----

Table 6. Liner diameter changes for various interference fits

Assembly no.	Interferences*	Liner diameter as rec'd	Liner diameter after OP No. 1**	Change in liner diameter	Liner diameter after OP No. 2**	Change in liner diameter	Total change
No. 1	0.004/0.002	0.5111	0.5104	-0.0007	0.5100	-0.0004	-0.0011
No. 2	0.002/0.002	0.5111	0.5107	-0.0004	0.5104	-0.0003	-0.0007
No. 3	0.003/0.002	0.5108	0.5101	-0.0007	0.5098	-0.0003	-0.0011

* Liner-sleeve, and sleeve-jacket, in that order.

**Op No. 1 - Sleeve shrunk onto liner.
Op No. 2 - Jacket shrunk onto sleeve/liner.

1. Place sleeve on assembly fixture and heat to 925°F for one houre in air recirculating oven

2. Remove fixture from furnace and assemble liner

3. Place assembly back in furnace (heat off - circulation on) and allow to cool to below 400°F

4. Face ends and grind sleeve OD concentric to liner bore and to size for proper interference fit with jacket

5. Fluorescent penetrant inspect

6. Heat jacket to 900°F by induction and assemble liner/sleeve subassembly

7. Fluorescent penetrant inspect

8. Assembly spacer and retainer

9. Thread breech end OD

10. Assembly muzzle end

11. Chamber

Figure 14. Test barrel assembly procedure

when subjected to actual firing conditions, the three barrel assemblies described in the previous section were test fired single shot from a test stand at the rate of one round per minute maximum, using .50 caliber ball ammunition. During the firing test, barrels were air cooled to maintain a temperature of less than 150 F. All barrels were tested and inspected in a manner similar to that outlined in table 7.

The primary focus of the firing test was to determine whether the smooth bore alpha silicon carbide liner would withstand the repeated thermal shock, pressure stresses, and chemical environment of the barrel. The projectiles to be fired were originally a slip fit with the liner ID in order not to impose additional physical stresses on the liner bore due to an interference fit with the projectile. Shrink fitting of the liner into the sleeve and jacket, however, caused the liner ID to decrease by 0.0007 - 0.0011 inches and become a slight interference fit with the projectile. Except where indicated, projectiles were polished to once again obtain a slip fit with the liner.

Assembly No. 1 -- Liner/Sleeve Interference = 0.004 inches

Assembly No. 1 (cracked during assembly) was test fired with 24 polished rounds followed by 100 unpolished rounds with no apparent damage to the liner ID surface. The crack width gradually widened as small quantities of material were removed from the crack surfaces and deposited in the bore in the form of a powdery residue. Firing on Assembly No. 1 was terminated after a total of 124 rounds when the crack had widened to a 1/8 inch gap at its widest point. The barrel was still performing satisfactorily when the test was terminated.

Measurements taken on rounds 10 and 11 indicated muzzle velocities of 2,800 ft. per sec. which compared favorably with readings taken on standard M2 barrels, despite the fact that the bullet has a travel to exit of 33 1/2 inches in the test barrel vs. 41 inches in the standard barrel. These velocity readings indicate with a high degree of confidence that full chamber pressure was developed in the test barrel. One of the most important observations to be made from the testing of Assembly No. 1 is that alpha silicon carbide liners will perform without catastrophic failure even after they are cracked.

Table 7. Barrel test and inspection procedure

Test fixture: .50 caliber test stand remotely fired
Mode of fire: Single shot
Rate of fire: One round per minute maximum
Cooling : Cool with air to maintain 105°F max.

Round	Characteristic	Inspection method	Frequency
0	Bore diameter Bore surface	Air gage Profilometer Borescope Dye penetrant	100% 100%
1-5	Bore surface	Borescope	100%
6-14	Bore surface	Visual	100%
15	Bore surface	Borescope	100%
16-24	Bore surface	Visual	100%
25	Bore surface	Borescope	100%
26-49	Bore surface	Visual	100%
50	Bore surface	Borescope	100%
51-99	Bore surface	Visual	100%
100	Bore surface	Borescope	100%
101-499	Bore surface	Visual Borescope	100% Every 50th
500th	Bore diameter Bore surface	Air gage Profilometer Borescope Dye penetrant	100% 100% 100% 100%
501-999	Bore surface	Visual Borescope	100% Every 50th
1000	Bore diameter Bore surface	Air gage Profilometer Borescope Dye penetrant	100% 100% 100% 100%

Assembly No. 2 -- Liner/Sleeve Interference - 0.002 inches

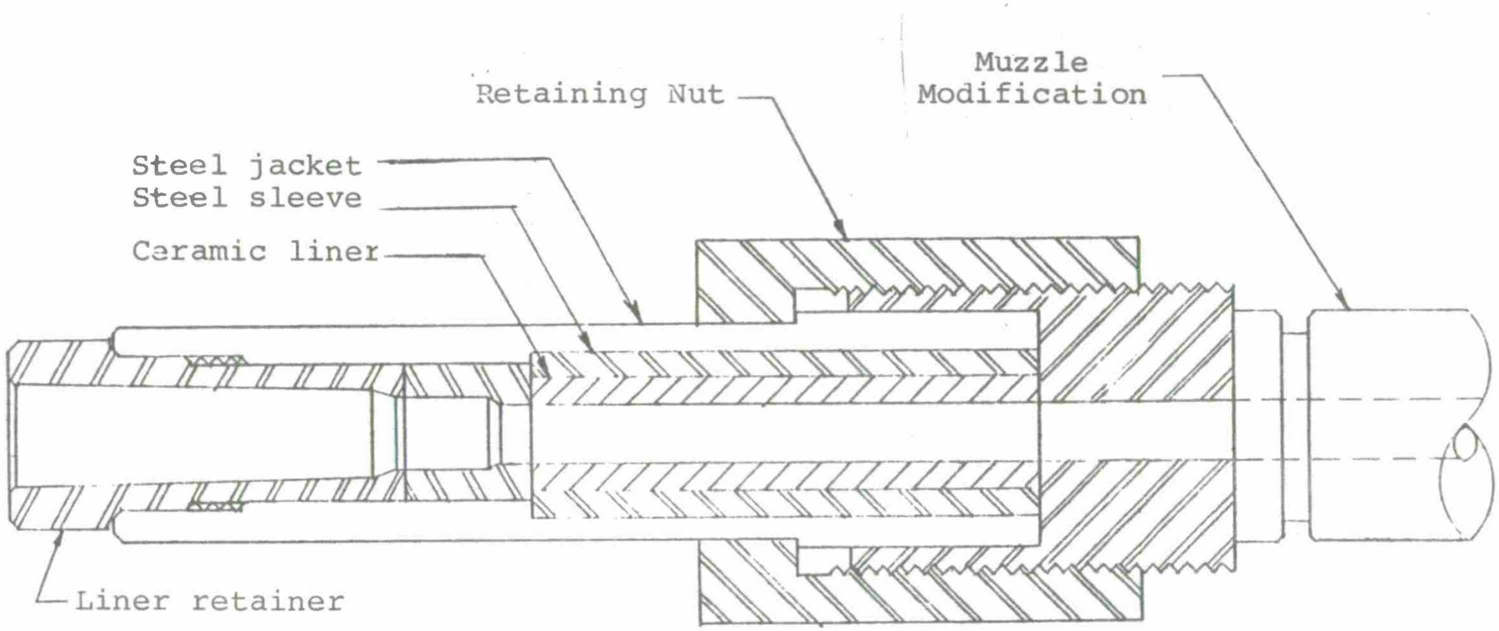
Assembly No. 2 was test fired exclusively with polished rounds. Bullet velocities were measured at 2,800 ft per sec on rounds 11 and 12 and a target group pattern was taken on rounds numbered 26 through 35 with satisfactory results. Firing continued with periodic bore scope examination through round 572 at which time the muzzle section of the test barrel separated from the breech section at the bottom of the 1.90 inch diameter counterbore. The liner and breech assembly were not damaged and firing was resumed using the forward section and retaining nut from Assembly No. 3. As firing progressed, the retaining nut and the threaded portion of the barrel just ahead of the nut were observed to be swelling. At the same time borescope inspection of the barrel revealed flakes of gilding metal at the forward end of the liner and at 715 rounds the forward end of the liner began to deteriorate. The barrel was disassembled and gilding metal was observed to be deposited over the entire front face of the breech section, apparently due to a lack of concentricity between the liner bore and the bore of the muzzle section, gilding metal was being shaved from bullets and forced into the minute gap between the end of the liner and the muzzle section. Liner damage was due either to the action of the gilding metal itself or the forcible cocking of the bullet as it exited the liner and entered the rifled bore.

These difficulties were corrected by making the retaining nut longer and thicker to provide more support for the muzzle section of the barrel, and by counterboring the first inch of rifled bore to accommodate any misalignment between the liner bore and rifling (see figure 15). The forward end of the breech section was faced back approximately 0.300 inch in order to remove the damaged area of the liner, and firing was resumed.

Firing was continued, with periodic cooling and examination by borescope until the round count equaled 1000. Visual and dye penetrant inspection revealed no damage.

Assembly No. 3 -- Liner/Sleeve Interference - 0.300 inch

Prior to test firing Assembly No. 3, the bore was honed slightly in order to achieve a slip fit with the bullets and thereby eliminate the need for polishing individual rounds. In the process, the forward half of the liner bore was mistakenly enlarged 0.001 to 0.002 inches larger than



Ceramic liner test barrel assembly
improved configuration

Figure 15. Test barrel configuration
improved configuration

the bullet diameter. (The bore diameter in the rear half of the liner was acceptable). Since additional hardware was unavailable and any attempt to start from scratch would involve excessively long lead time, the decision was made to test this assembly as is. A target group of five rounds was taken at rounds 16 through 20 with satisfactory results. At round 375, a circumferential crack was observed 1/8 inch forward of the rear face of the liner and the test was terminated at this point. The most probable cause of the liner cracking was nonuniform radial stresses developed during assembly.

A test summary for each barrel is shown in tables 8 through 10.

Liner bore diameters were consistently observed to decrease a slight amount as firing progressed (table 11). This was attributed to the formation of a deposit on the bore surface. The character of this deposit is being investigated further. Surface roughness remained essentially unchanged during the course of the test.

CONCLUSIONS

The following conclusions are supported by the results of this study:

1. Alpha silicon carbide can be successfully shrink fitted into a Cr, Mo, V steel sleeve and assembled as a .50 caliber M2 smooth bore barrel liner.

2. Alpha silicon carbide shows no evidence of erosion after 1,000 rounds when tested as a modified smooth bore .50 caliber M2 barrel liner under room temperature single shot firing conditions.

3. Alpha silicon carbide liners appear sensitive to residual stress gradients imposed during assembly and additional work is required to eliminate end cracking conditions.

4. Alpha silicon carbide liners maintained under compression will not immediately fail catastrophically even with a transverse circumferential crack running completely through its cross section.

5. Alpha silicon carbide has potential as an erosion resistant smooth bore barrel liner.

Table 8. Test Summary - Assembly No. 1 (0.004 inches interference)

Number of rounds	Observations
0	Circumferential crack observed 1/4 inch from muzzle end
10 - 11	Velocity measured at 2,800 ft/sec Slow growth of crack width
25	Began firing unpolished round Continued widening of crack
124	Test terminated. No unusual ID damage due to unpolished rounds No discernable size change

Table 9. Test Summary - Assembly No. 2(0.002 inches interference)

Number of rounds	Observations
11 - 12	Velocity measured at 2,800 ft/sec
26 - 35	Target group pattern OK
572	Front end of test barrel failed Liner and breech assembly not damaged Installed new muzzle end and resumed firing
715	Gilding metal being shaved from projectiles due to misalignment of liner bore and muzzle section Muzzle face of liner damaged Faced off 0.300 inch to remove damage Free bored muzzle section ID for 1 inch to allow for misalignment
1000	Test terminated

Table 10. Test Summary - Assembly No. 3(0.003 inch interference)

Number of rounds	Observations
0	Honed liner bore to allow firing of unpolished rounds Observed circumferential crack 1/4 inch from muzzle end after honing Faced off 0.300 inch to remove crack
16 - 20	Target group pattern OK
375	Observed circumferential crack 1/8 inch from breech face of liner Test terminated

Table 11. Effect of firing tests on a liner bore diameter and surface finish

Assembly no.	Interferences**	Round no.	Bore diameter	Bore roughness (r.m.s.)
1	0.004/0.002	0	0.5100	3.5
		124	0.5098	2
2	0.002/0.002	0	0.5104	3
		100	0.5103	5 - 17 *
		572		4
		715	0.5102	
		1000	0.5096	7
3	0.003/0.002	Not measured - bore was oversize		

* Shiny and dull area respectively
**Liner-sleeve and sleeve jacket in that order

6. The feasibility of employing ceramic material as a smooth bore liner in a small to medium caliber gun barrel has been established.

RECOMMENDATIONS

The study results provide sufficient confidence in the application of ceramic material to justify further investigation. It is recommended that as a next step, follow-on work be undertaken to:

1. Analyze and solve the liner end cracking problem through modifying the liner sleeve geometry or through the use of a compliant layer at the interface.

2. Investigate liner/sleeve geometry and interference fits for use at elevated temperatures.

3. Evaluate the alpha silicon carbide liner under automatic firing and elevated temperature conditions. Future testing to include measurement of chamber pressure to verify that full pressure has been achieved.

4. Investigate the possibility of rifling the liner or modifying the rifling in the tube to be compatible with a smooth bore liner.

5. Investigate the concept in 20 mm or 30 mm barrel which would subject the material to the more severe environment of large calibers.

BIBLIOGRAPHY

1. Timoshenko, S., Strength of Materials; Volume II, 3rd Edition, March 1956, unclassified.

2. Wang, C.T., Applied Elasticity 1st Edition, 1953, unclassified.

3. Metals and Ceramics Information Center, Battelle Memorial Institute, Columbus Ohio.

   a) "Engineering Property Data on Selected Ceramics"; Volume I. Nitrides.

   b) "Current Awareness Bulletin," September 14, 1979.

   c) "Evaluation of Si_3N_4 and SiC In a Simulated Gas Turbine Environment," 1 May 9, 1979.

   d) "Excerpts from Section 4.3 of Ceramics Data Book."

4. KBI-AME Inc., Products Data Book, "Silicon Nitride," File #600 PDI-13-1977.

5. The Carborundum Company

   a) "Substitution of Ceramic for Ductile Materials in Design," June 76.

   b) "Mechanical Response of High Performance Silicon Carbide," August 1976.

   c) "Thermo Mechanical Properties of Sintered Alpha Silicon Carbide," March 1977.

   d) "Sintered Alpha Silicon Carbide: Some Aspects of the Microstructure - Strength Relationships," September 1977.

   e) "Crack Propogation in Sintered Alpha Silicon Carbide," September 1977.

   f) "Technical Information-Sintered Alpha Silicon Carbide," April 1978.

DISTRIBUTION LIST

Defense Technical Information Center
ATTN: Accessions Division (2)
Cameron Station
Alexandria, Virginia 22314

Office of the Chief of Research
and Development
ATTN: CRDRPG
Washington, D.C. 20310

Commanding General
U.S. Army Materiel Development
and Readiness Command
5001 Eisenhower Avenue
Alexandria, Virginia 22333

Commanding General
U.S. Army Armament Research
and Development Command
ATTN: DRDAR-LCA (10)
DRDAR-QAR (1)
DRDAR-SF (1)
DRDAR-TSS (5)
DRDAR-GCL (1)
Dover, New Jersey 07801

Director
U.S. Army Materiel Systems Analysis Activity
ATTN: DRXSY-MP
Aberdeen Proving Ground, MD 21005

Commander
U.S. Army Armament Research
and Development Command
Weapons Systems Concepts Team
ATTN: DRDAR-ACW
APG, Edgewood Area, MD 21010

Commander/Director
Chemical Systems Laboratory
U.S. Army Armament Research and
Development Command
ATTN: DRDAR-CLJ-L
APG, Edgewood Area, MD 21010

Director
Ballistics Research Laboratory
U.S. Army Armament Research
and Development Command
ATTN: DRDAR-TSB-S
DRDAR-BLP/ Dr. J. R. Ward
Aberdeen Proving Ground, MD 21005

Chief
Benet Weapons Laboratory, LCWSL
U.S. Army Armament Research
and Development Command
ATTN: DRDAR-LCB-TL
Watervliet, NY 12189

Commander
U.S. Army Armament Materiel
Readiness Command
ATTN: DRSAR-LEP-L
Rock Island, IL 61299

Director
U.S. Army TRADOC Systems Analysis Activity
ATTN: ATAA-SL
White Sand Missile Range, NM 88002

Director
U.S. Army Materiels and Mechanics
Research Center
ATTN: Dr. J. McCauley
Watertown, MA 02172